Published in final edited form as:

Appl Phys A Mater Sci Process. 2014 January 1; 114(1): 209–214. doi:10.1007/s00339-013-8106-4.

High average power Yb:CaF₂ femtosecond amplifier with integrated simultaneous spatial and temporal focusing for laser material processing

J. Squier¹, J. Thomas^{1,2}, E. Block¹, C. Durfee¹, and S. Backus^{3,4}

J. Squier: jsquier@mines.edu

¹Center for Microintegrated Optics for Advanced Bioimaging and Control, Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA, Ph: 303 384-2385, Fax: 303 273-3919

²Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

³KMLabs Inc., Research and Development Department, 1855 S 57th Ct, Boulder, Colorado 80301, USA

⁴Colorado State University, Department of Electrical and Computer Engineering, Ft. Collins, Colorado 80523, USA

Abstract

A watt level, 10-kilohertz repetition rate chirped pulse amplification system that has an integrated simultaneous spatial and temporal focusing (SSTF) processing system is demonstrated for the first time. SSTF significantly reduces nonlinear effects normally detrimental to beam control enabling the use of a low numerical aperture focus to quickly treat optically transparent materials over a large area. The integrated SSTF system has improved efficiency compared to previously reported SSTF designs, which combined with the high repetition rate of the laser, further optimizes its capability to provide rapid, large volume processing.

Keywords

chirped pulse amplification; simultaneous spatial and temporal focusing

1. Introduction

Until recently, material processing with femtosecond pulses within transparent materials was primarily limited to focusing conditions that employed relatively high numerical aperture (~0.2–0.5 NA) refractive optics[1]. Tight focusing conditions are necessary given the intensities required to produce Type 1–3 material modifications or to selectively ablate within optically transparent materials. In addition, the large angles of the focused cone of light (12 to 30 degree half angles in air) achieved with these objectives are useful in order to help diminish nonlinear effects such as self-focusing and enable controlled production of features. Corresponding to these high angles, however, is a small focal spot, from 2 to 6 μm in diameter for the range of focusing conditions considered here. These parameters have important consequences. For processing large volumes, high repetition rate laser systems with fast scanning systems are a necessity. In addition, the working distances of the high NA optics (~0.5 to 6 mm) can result in restrictions on the three-dimensional volume that can be practically addressed.

Simultaneous spatial and temporal focusing (SSTF)[2, 3] enlarges the parameter space where three-dimensional femtosecond material processing can be effective in all the aforementioned regimes. For example, low numerical aperture beams (e.g., 0.03) can be effectively employed enabling large spot sizes ($>20\text{ }\mu\text{m}$) with long working distances ($>25\text{ mm}$). SSTF is able to achieve this broader range of focusing conditions as a result of the fact that only at the focal plane is the pulse transform-limited in time and diffraction-limited in space. Out-of-focus, the pulse is both spatially and spectrally chirped resulting in a dramatic reduction in axial intensity[2, 3]. This spatial and temporal spreading of the beam successfully mitigates nonlinear effects such as self-focusing and is the driving force that enables effective use of low NA beams deep within transparent materials for the first time[4].

A typical geometry for creating an SSTF beam that can handle the fluence generated by high-repetition rate, $100\text{ }\mu\text{J}$ (and higher) femtosecond amplifier is a standard Tracey grating compressor arranged in a single pass configuration followed by a focusing optic. Single-passing the SSTF compressor results in an output beam with transverse spatial chirp. An important characteristic of this SSTF configuration, compared to single grating designs, is that the beam retains a symmetric profile when the grating is used at an angle of incidence (AOI) other than the Littrow angle. The collimated, spatially chirped output can be considered as a continuum of wavelength-dependent beamlets with amplitudes modulated by the pulse spectrum. These low NA beamlets are eventually recombined with a higher NA optic as depicted in Fig. 1. The beamlet diameter and focal length of the focusing optic ultimately sets the $f/\#$ of the system and hence the spot size at the target material. The ratio of the input beam diameter w_{in} (incident on the first grating) to the output beam diameter w_{in} (after the second grating) is an important metric known as the beam aspect ratio, that can be used to determine how the focused axial intensity profile will scale[5]. A system with no spatial chirp has a $=1$, while an SSTF system has >1 . (Notably, while the work and results presented here are for low NA SSTF beams, a detailed analysis of SSTF beams at high NA has been done by Yew *et al*[6].)

The impact of is illustrated in Table 1 through simple back-of-the-envelope calculations using the notation and equations of Durfee *et al*[5]. Remarkably, low NA SSTF beams (e.g., 0.03 NA for the beamlets) that produce focal spots in the range of $15\text{--}30\text{ }\mu\text{m}$, and have a from ~ 7 to 13 respectively, can have confocal parameters (axial intensity, FWHM) that are virtually identical to a standard beam focused to a $3\text{ }\mu\text{m}$ spot size. Notably, for this combination of spot size and the focal area is increased by a factor of 5 to 10 times and the cone angle for the SSTF beams is slightly greater than that of the standard focus in the spatially chirped direction and is less than the standard focus in the non-chirped dimension. Once again in SSTF, the beamlet size and focal length of the focusing optic determines the focal spot size, while the spatial chirp () at the entrance pupil of that same optic sets the axial sectioning.

Assuming a linear scan strategy, the larger focal spot with SSTF translates to a proportionate reduction in processing time. This clearly implies that the pulse fluence be maintained over the larger focal area meaning that the per/pulse energy be scaled accordingly. This is readily done with state-of-the-art femtosecond chirped pulse amplification systems that are capable of delivering 10^3 's to 10^4 's of microjoules at 10^3 's of kHz repetition rates ($>1\text{ W}$ average powers).

To date SSTF has been exploited in several novel laser-processing applications involving material modifications and ablation of biological materials. Kim *et al*.[7] and Y. -C. Li *et al*. [8] have used SSTF to do rapid multiphoton lithography and microfabrication. He *et al*.[9] demonstrated the production of microfluidic channels 2 mm in length using SSTF to treat

the material, followed by etching. What is particularly relevant in this study was that SSTF was used to re-shape the laser modified volume in three-dimensions. This is one of the intriguing aspects of SSTF alluded to in our discussion of Table 1. Vitek *et al.* demonstrated that controlled ablation at depth was possible using low NA beams for the first time with SSTF[4]. Indeed, the channels produced through backside ablation using SSTF had superior aspect ratios compared to front side laser ablation or channels produced via chemical etching. Vitek *et al.* also demonstrated that pulse front tilt, which can be selectively controlled with SSTF, can result in non-reciprocal material modification in bulk or on the surface[10]. Finally, Block *et al.*[11] have recently shown that selective ablation of biological tissue can be performed with SSTF even when operating well above the ablation threshold. Notably Block *et al.* demonstrated how the focal plane shifts as a result of self-focusing in a standard geometry and results in large, uncontrolled ablation zones. With SSTF on the other hand, the focal plane remains fixed even when operating ~58 times above the ablation threshold, and the ablation zone remains strictly confined.

This work builds on the considerable potential of SSTF. In particular we demonstrate a novel SSTF compression system that is imbedded within a high repetition rate Yb:CaF₂ chirped pulse amplification system. As a result of this integrated design, SSTF laser material processing can be performed with the direct output of the laser for the first time. A fully integrated, high average power SSTF femtosecond laser system is a new paradigm for rapid three-dimensional laser material processing and opens the door to high-speed surgeries that are presently prohibitive. It is also an important step towards an implementation of SSTF for commercial applications in general.

II. Experimental set-up

The chirped pulse amplification system is of a direct-diode pumped architecture. The 150-fs seed pulse is created by a Yb fiber oscillator (YFi, KMLabs Inc.) which is based on a normal dispersion configuration (ANDi Ultrafast Laser [12]). These systems operate at 60 MHz repetition rate, and produce average powers on the order of 0.5–1.0 Watt. The pulse is stretched using a custom fiber stretcher. The stretched pulse seeds a Yb:CaF₂ regenerative amplifier that is pumped at 976 nm[13]. The amplifier is tuned to run at repetition rates from 1 to 400 kHz. Fig. 2 is a measure of the amplified pulse compressed through a standard double-pass grating compressor. The pump efficiency is 73% for Yb:CaF₂ crystals doped to 3%. For 19 Watt of pump power, 13.9 Watts is absorbed, resulting in 2.5 Watts of power after compression, 150 fs pulses with an $M^2 = 1.1$.

In all previous experiments with SSTF, a second pair of gratings was used in conjunction with the amplifier compressor to create the spatially chirped SSTF beam[4, 10, 11]. While effective, this makes the ultimate implementation of SSTF more complicated than it needs to be, and certainly less efficient. Here we combine the two processes in a single integrated unit for the first time. A single pass compressor design compensates for the stretcher and the residual dispersion picked up in the amplifier. The resultant output of the compressor is a spatially chirped beam with a slight negative chirp to compensate for the refractive focusing optics upstream of the compressor. The overall system schematic is shown in Fig. 3.

The transmission grating (LightSmyth Technologies) has a groove density of 1000 lines/mm and a clear aperture of 82 by 19 mm. Used at the Littrow angle of 31 degrees it has >94% diffraction efficiency. This high throughput is a key point where integration of SSTF into the CPA architecture becomes beneficial. Traditional grating compressors are double-passed resulting in efficiencies of ~78% (for 94% diffraction efficiency) while the SSTF compressor is single-passed which improves the throughput to ~88% (again for 94% diffraction efficiency). Obviously, this gain is more pronounced the lower the diffraction

efficiency of the compressor grating becomes. The geometry is also relatively compact. The distance from the grating to the dihedron is ~50 cm. The dihedron reflector is on a translation stage so that the dispersion can be smoothly varied and the pulse width at focus be readily optimized.

Finally, for material processing a 75 mm focal length lens is used, and the target material is rastered beneath the beam. A three-axis specimen scanning stage is used (Aerotech, Inc. ANT130-110-XY/ANT130-060-L-Z). The stages can be scanned a distance of 11 cm in x-y (6 cm in z) at speeds of up to 35 cm/s (20 cm/s in z).

III. Results

This is the first SSTF micromachining workstation that incorporates refractive optics into the design. Refractive lenses can be complicated to work with in SSTF geometries as they are being employed using image and object conjugates that the original lens design was not targeting. As such, it is highly recommended that the user critically evaluate any refractive optic they intend to use in an SSTF design through a simple ray-tracing analysis. The complications of focusing through refractive optics are evaluated here for the lens system shown in Fig. 3.

The focusing optic is a 75 mm achromat (Thor Labs, AC508-075-B), with an input beamlet diameter of 2.5–3 mm for a beam aspect ratio, β , of approximately 5 for these experiments. The system is presently configured to switch between standard focusing and SSTF limiting the beam aspect ratio. Future work will involve increasing to >20 . The clear aperture of all optics was designed with this expansion in mind. The focal plane location is optimized to produce the minimal root mean square spot radius with the central (1.045 μm) and extreme wavelengths (1.035 μm and 1.055 μm) weighted equally. The ray fan plot is for the beamlets at 1.035 μm , 1.045 μm , and 1.055 μm . The net spot size is minimized with a small amount of defocus. The off-axis beamlets pick up astigmatism and coma.

The Gaussian beam size as a function of wavelength at the focal plane is depicted in Fig. 4. It has been calculated for the optical elements described above using the Gaussian beam analysis of the raytracer. An input beamlet diameter of 2.5 mm has been assumed. The impact of the aberrations are evident as the beamlet size for wavelengths relative to the central wavelength, 1.045 μm (where the spot radius is 19 μm), decreases for both shorter and longer wavelengths in the x-plane, and increases monotonically in the orthogonal (y-plane) over the same wavelength range.

Borosilicate slides (Esco Products, #R230110) were machined with this focal spot using 90 μJ per pulse at a 10 kHz repetition rate. Samples were ablated on both the front and back surface. Notably, controlled back surface ablation is not possible without SSTF under these conditions. The slides used on this experiment were 1 mm thick. For the low NA beamlets used in SSTF, aberrations have shown to play a role, but only with much thicker samples such as used in [10]. It should be noted that even in this much thicker sample (6 mm), Vitek et al. still demonstrated SSTF backside machining without any corrective optics.

Dark field microscopy was used to examine the samples. The debris outside the channel was used to establish a common imaging plane to compare backside and front surface characteristics. What is immediately apparent is that with backside ablation (Fig. 5a) it is straightforward to find conditions under which a thin layer of material is uniformly removed even when ablating with fluences well above the ablation threshold as was done here. Once a thin layer is removed, successive shots are into air and cutting in the axial direction is clamped. Here, the width of the backside channels of ~40 micrometers agrees with the previously calculated spot dimensions. These are the conditions identified by Vitek et al.[4]

for creating high aspect ratio channels. For front surface ablation at the same fluence and sample translation speed a deeper channel is created as evident by the through focus image series in Fig. 5. Successive shots are able to continuously remove lower lying material. As a result, the channel develops the classic 'V' shape cross sectional profile (Fig. 5b). The resulting channels are significantly wider than the spot diameter.

Finally the translation speeds were varied in this first initial study. All other parameters were kept constant including material type, focal spot size, energy and pulse duration. Fig. 6 shows dark field images of channels cut on the front surface at speeds of 1 mm/s, 5 mm/s and 11 mm/s respectively. Material was readily ablated at all speeds. Typical writing and laser parameters of our SSTF system are summarized in table 2, where they are compared with a previous setup [10]. Most remarkable is an improvement of writing speed by a factor of 200 compared to our previous SSTF results in similar materials [10]. Notably these speeds make it possible to create complex microfluidic devices, for example, that were previously prohibitive as a result of the slow writing speeds.

IV. Conclusion

In summary, this work demonstrates the first high average power, femtosecond laser processing system with integrated SSTF delivery. By incorporating SSTF directly into the CPA architecture the system efficiency is improved, and the parameter space under which three-dimensional laser processing can be performed is enlarged. For example, selective ablation through the backside of optically transparent materials is possible, and material modification within the bulk with low NA beams is enabled. This is the first transmissive SSTF geometry that combines both transmission gratings and refractive optics making a system that is straightforward to construct and extremely practical to implement.

Finally, future work with this system will involve significantly extending the beam aspect ratio, , of the system. This has the intriguing possibility of making it possible to reshape the three-dimensional focal volume that can be treated. As such, SSTF represents a new paradigm in rapid three-dimensional laser processing of materials and the treatment of biological systems.

Acknowledgments

This work was funded by the National Institute of Biomedical Imaging and Bioengineering under the Bioengineering Research Partnership EB-003832, and the US Air Force Office of Scientific Research under program FA9550-12-1-0482. Jens Thomas is supported by the Carl-Zeiss-Foundation.

References

1. Itoh K, Watanabe W, Nolte S, Schaffer CB. Ultrafast processes for bulk modification of transparent materials. *MRS bulletin*. 2006; 31:620–625.
2. Oron D, Tal E, Silberberg Y. Scanningless depth-resolved microscopy. *Opt Express*. 2005; 13:1468–1476. [PubMed: 19495022]
3. Zhu G, van Howe J, Durst M, Zipfel W, Xu C. Simultaneous spatial and temporal focusing of femtosecond pulses. *Opt Express*. 2005; 13:2153–2159. [PubMed: 19495103]
4. Vitek DN, Adams DE, Johnson A, Tsai PS, Backus S, Durfee CG, Kleinfeld D, Squier JA. Temporally focused femtosecond laser pulses for low numerical aperture micromachining through optically transparent materials. *Opt Express*. 2010; 18:18086–18094. [PubMed: 20721196]
5. Durfee CG, Greco M, Block E, Vitek D, Squier JA. Intuitive analysis of space-time focusing with double-ABCD calculation. *Opt Express*. 2012; 20:14244–14259. [PubMed: 22714487]
6. Yew EYS, Sheppard CJR, So PTC. Temporally focused wide-field two-photon microscopy: Paraxial to vectorial. *Opt Express*. 2013; 21:12951–12963. [PubMed: 23736515]

7. Kim D, So PTC. High-throughput three-dimensional lithographic microfabrication. *Opt Lett*. 2010; 35:1602–1604. [PubMed: 20479822]
8. Li YC, Cheng LC, Chang CY, Lien CH, Campagnola PJ, Chen SJ. Fast multiphoton microfabrication of freeform polymer microstructures by spatiotemporal focusing and patterned excitation. *Opt Express*. 2012; 20:19030–19038. [PubMed: 23038543]
9. He F, Xu H, Cheng Y, Ni J, Xiong H, Xu Z, Sugioka K, Midorikawa K. Fabrication of microfluidic channels with a circular cross section using spatiotemporally focused femtosecond laser pulses. *Optics Letters*. 2010; 35:1106–1108. [PubMed: 20364232]
10. Vitek DN, Block E, Bellouard Y, Adams DE, Backus S, Kleinfeld D, Durfee CG, Squier JA. Spatio-temporally focused femtosecond laser pulses for nonreciprocal writing in optically transparent materials. *Opt Express*. 2010; 18:24673–24678. [PubMed: 21164813]
11. Block E, Greco M, Vitek D, Masihzadeh O, Ammar DA, Kahook MY, Mandava N, Durfee C, Squier J. Simultaneous spatial and temporal focusing for tissue ablation. *Biomed Opt Express*. 2013; 4:831–841. [PubMed: 23761847]
12. Chong A, Buckley J, Renninger W, Wise F. All-normal-dispersion femtosecond fiber laser. *Opt Express*. 2006; 14:10095–10100. [PubMed: 19529404]
13. Druon F, Ricaud S, Papadopoulos DN, Pellegrina A, Camy P, Doualan JL, Moncorgé R, Courjaud A, Mottay E, Georges P. On Yb:CaF₂ and Yb:SrF₂: review of spectroscopic and thermal properties and their impact on femtosecond and high power laser performance [Invited]. *Opt Mater Express*. 2011; 1:489–502.

Fig. 1.
Schematic of SSTF beamlet combining.

Fig. 2. Measured second harmonic generation FROG trace while operating at 50 kHz. Pulse width measures 150 fs.

Fig. 3. System schematic. A single grating is double-passed to compensate for the net dispersion of the stretcher, amplifier and focusing lens. The output results in a collimated spatially chirped beam.

Fig. 4. Beam size as function of wavelength at the focal plane. The waist size is nominally 19 μm at the central wavelength, 1.045 μm .

Fig. 5.
(a) Back surface ablation through 1 mm thick borosilicate sample. Translation speed was 1 mm/s. (b) Through focus series of front surface ablation for identical conditions. Scale is same in all photos.

Fig. 6. Dark field images of channels cut at different rates. Starting from left, 1 mm/s, 5 mm/s, and 11mm/s.

Table 1

Low numerical aperture SSTF beams (rows 1 & 2) are compared to a standard focus (row 3). The wavelength used for these calculations is $1.040\text{ }\mu\text{m}$.

Type of focus	Waist diameter (μm)	Beam aspect ratio	Confocal beamlet parameter z_r (μm)	Axial FWHM Radius $z_{1/2}$ (μm)
SSTF	30	13.2	2718	27
SSTF	15	6.6	680	27
Standard	3	1.0	27	27

Table 2

Comparison of laser and writing parameters with a conventional SSTF system [10].

	Vitek et al. [10]	This work
Pulse energy (μJ)	25	90
Repetition rate (kHz)	1	10
Spot radius (μm)	17.5	19
Laser fluence (J/cm^2)	2.6	7.9
Writing speed (mm/s)	0.05	10
Laser shots per spot	700000	38000